AN APPARATUS for FORMING WATERDROPS

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AN APPARATUS for FORMING WATERDROP

By Robert S. Palmer, *agricultural engineer, Soil and Water Conservation Research Division, Agricultural Research Service, and adjunct professor of agricultural engineering, University of New Hampshire* [1]

A study was initiated to develop a drop-forming device that can be used to furnish a particular size of waterdrop at a controlled rate for use in the design of a laboratory rainfall simulator. In carrying out this objective, interest was focused on drops formed by the disintegration of water jets.

Those persons interested in the mechanics of waterdrops will find the survey by Lane and Green (*5*) [2] to be valuable. The bibliography prepared by Pearson and Martin (*9*) is an essential reference for persons interested in the simulation of rainfall. Investigations concerned with the breakup of liquid jets are reviewed by Richardson (*11*) and by Birkhoff and Zarantonello (*1*).

A number of investigators have developed apparatus of varying complexity to gain some understanding of waterdrop phenomena in the laboratory. Similarly, the drop-forming device that is described here is for use in a laboratory rainfall simulator. By subjecting various soils to simulated rainfall under controlled conditions, it is hoped that a greater understanding of the mechanics of soil erosion and runoff will result.

DESIGN OF A DROP-FORMING DEVICE

The laboratory rainfall simulator has two principal components: an application unit and a reference plane. A rotating applicator will hold drop-forming devices in a predetermined arrangement under varying heads of water. It will discharge drops onto soil pans situated on a reference plane. The distance between the applicator and the reference plane is adjustable, to permit variations in the height of fall of the drops and thereby vary their energy at impact.

[1] Edwin A. Harre, conservation engineering technician, offered helpful suggestions and carried out the procedures described in this report. The author also expresses his appreciation to Dwight D. Smith, assistant director, Soil and Water Conservation Research Division, Agricultural Research Service. Other persons whose discussions aided in the presentation of the results are Edwin L. Cox, biometrician, Agricultural Research Service; Owen B. Durgin, statistician, New Hampshire Agricultural Experiment Station; and Harold J. Zoller, professor of civil engineering, University of New Hampshire.

[2] Italic numbers in parentheses refer to Literature Cited, p. 15.

The apparatus designed to aid in the development of a suitable drop-forming device is essentially a water column with an opening in the bottom to accept various gages and lengths of stainless steel tubing. A static head of the desired level is maintained in the water column by means of a double-siphon system.

The drops formed are simultaneously counted and collected in weighing bottles, while the collection period is automatically timed. The average size of the drops collected from the tubing can be determined by dividing the total number of drops counted into the total weight of the discharge water. The nominal drop diameter is then calculated from the average weight of the collected drops. The nominal drop diameter is the diameter of a drop whose spherical volume would contain the weight of water in a given drop. A description of the drop counting and collecting apparatus is given in the appendix, p. 17. Dimensions of the stainless steel tubing used in this study, with allowable tolerances, are shown in table 1. As the tubing gage number increases, the internal diameter of the tubing decreases.

TABLE 1.—*Standard gages and tolerances of stainless steel tubing for figure 11, appendix*

Gage	Outside diameter (O.D.)		Nominal wall		Inside diameter (I.D.)	
	Size	Tolerance	Size	Tolerance		
	Inch	*Inch*	*Inch*	*Inch*	*Inch*	*Centimeter*
8	0.165	±0.001	0.015	±0.001	0.135	0.3430
10	.134	±.001	.014	±.001	.106	.2692
11	.120	±.001	.013	±.001	.094	.2388
12	.109	±.001	.012	±.001	.085	.2159
13	.095	±.001	.012	±.001	.071	.1803
14	.083	±.001	.010	±.001	.063	.1600
15	.072	±.0005	.009	±.0005	.054	.1371
16	.065	±.0005	.009	±.0005	.047	.1193
17	.059	±.0005	.009	±.0005	.041	.1066
18	.050	±.0005	.0085	±.0005	.033	.0838
19	.0425	±.0005	.00775	±.0005	.027	.0686
20	.0355	+.0005 −0	.00625	+0 −.0005	.023	.0584
21	.032	+.0005 −0	.00625	+0 −.0005	.0195	.0495
22	.028	+.0005 −0	.00625	+0 −.0005	.0155	.0394
23	.025	+.0005 −0	.00625	+0 −.0005	.0125	.0317
24	.022	+.0005 −0	.00525	+0 −.0005	.0115	.0292

Early experiments provide some insight as to what to expect as the pressure head above a small tube is increased. Harkins and Brown (*4*) have shown that at very low heads, when the inertial and viscous forces acting at the tip of the orifice are nearly in equilibrium, the relation of the weight of the drop formed (at about 1 drop per 5

minutes) to that of an ideal drop may be used to determine the surface tension of a liquid. As the head is increased, larger drops form at a faster rate and a greater proportion of the ideal drop develops. Rayleigh (*10*) theorized that the discharge ultimately forms a cylindrical liquid column that becomes unstable when its length exceeds its circumference. Any disturbance with a wavelength greater than the circumference of the liquid column or jet that acts at the orifice will increase in amplitude as it travels downward until the sides of the jet come together, destroying its continuity and forming individual drops. Under higher heads Haenlein (*3*) has shown that the jet deteriorates and complete disintegration or atomization occurs at the orifice.

Experiments, in which various gages and lengths of stainless steel tubing were used, were conducted with heads that caused jet flow. It was found that jet discharge through the tubing could be used to produce drops with an average diameter of 1.24 to 4.44 mm., but the discharge occurred at too high a rate to be used for simulating rainfall in the laboratory. For example, a 7.22-cm. length of 11-gage tubing under a 19.9-cm. head discharges 284 grams of water per minute while forming drops with an average diameter of about 3.0 mm. The discharge from this one orifice is equivalent to 0.6 cubic foot of water per hour.

Attempts to combine a length of small diameter tubing (to control the rate of discharge) with a length of larger diameter tubing (to form drops) were not successful. Either the results were not consistent, or the desired drop size and discharge could not be achieved. However, a graded tube, made up of lengths of tubing in a graded series, performed well. Flow was controlled by means of a small-diameter length of tubing, and the issue was passed successively into larger diameter lengths of tubing. Each length of tubing was 1.5 cm. long; therefore, the length of the graded tube was increased as larger diameter segments were added to it. In this manner the discharge was materially decreased.

Flow into the smaller diameter tubes is greater when they are components of a graded tube. For example, with a head of 9.5 cm., a 1.5-cm. length of 22-gage tubing will discharge 1.86 grams per minute, whereas the discharge rate from a 22 to 8 graded tube is 2.35 grams per minute. The 22 to 8 graded tube indicates that the initial section is a length of 22-gage tubing and the terminating section is a length of 8-gage tubing. If the 8-gage section is increased in length, the rate of drop formation increases and the size of drops becomes smaller. The dimensions of a representative graded tube (fig. 12) used in this study and comments on its fabrication appear in table 4 of the appendix, p. 19.

As the head above the graded tube is increased, both the average drop size and drop count increase. Figure 1 shows how the discharge rate in grams per minute increases as the centimeters of head are increased above graded tubes with an 8-gage outlet. Figure 2 shows that the drop count per minute also increases with head for the same graded tubes. When the head is increased above each graded tube of a grouping (table 4, appendix, p. 19) with the same size exit orifice, the relation of drop diameter to discharge seems to conform to a definite pattern. The average size of the drops formed increases with discharge until some critical value is reached. Thereafter, the drops

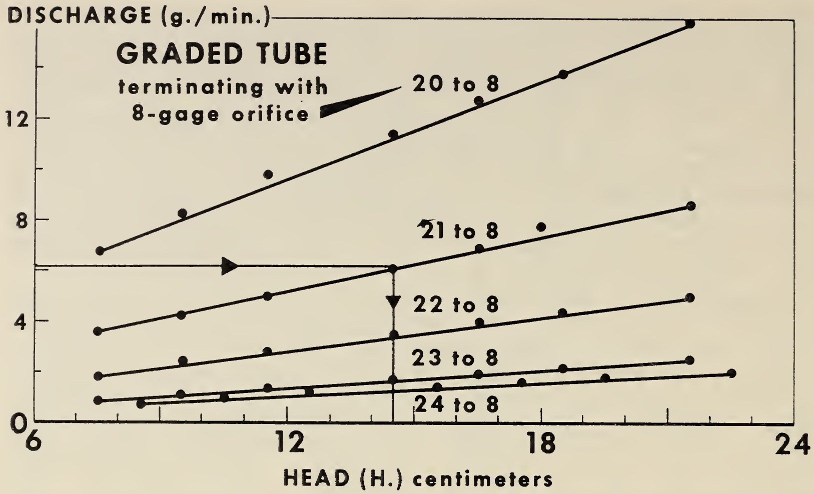

Figure 1.—Relation of discharge rate to height of head, when graded tubes terminate with an 8-gage orifice.

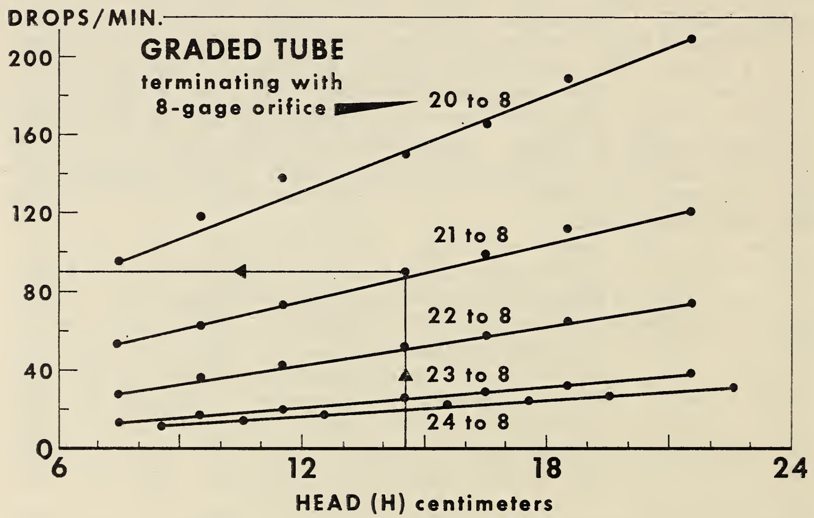

Figure 2.—Relation of drop count to height of head, when graded tubes terminate with an 8-gage orifice.

become smaller as the drop count rapidly increases, until a jet forms.

In figure 3, drop diameter is plotted against discharge on semilog paper, to illustrate this phenomenon. A maximum head of 15 centimeters above the entrance orifice was used, which limited the extent of the curves for the smaller graded tubes. Jet flow occurred from graded tubes ending with 16-gage and 17-gage orifices. Sug-

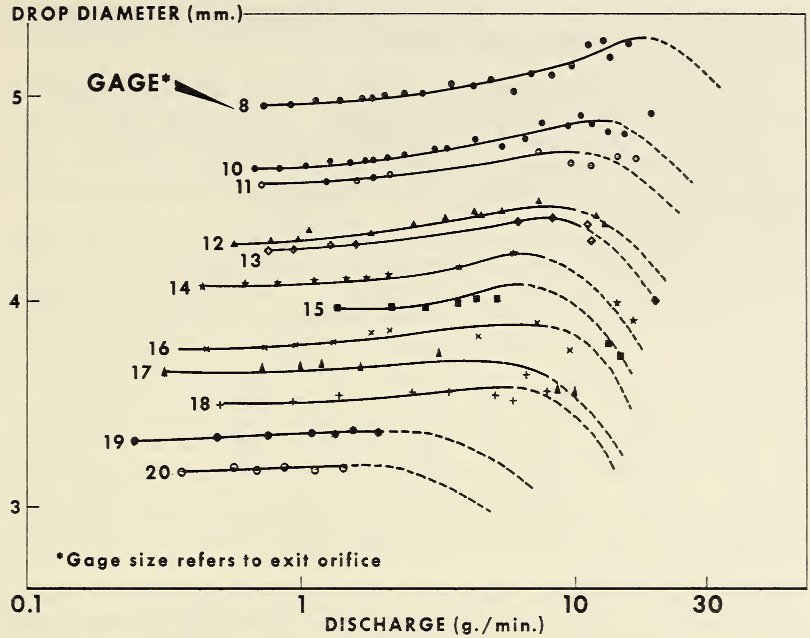

FIGURE 3.—Relation of drop diameter to discharge for various groupings of graded tubes.

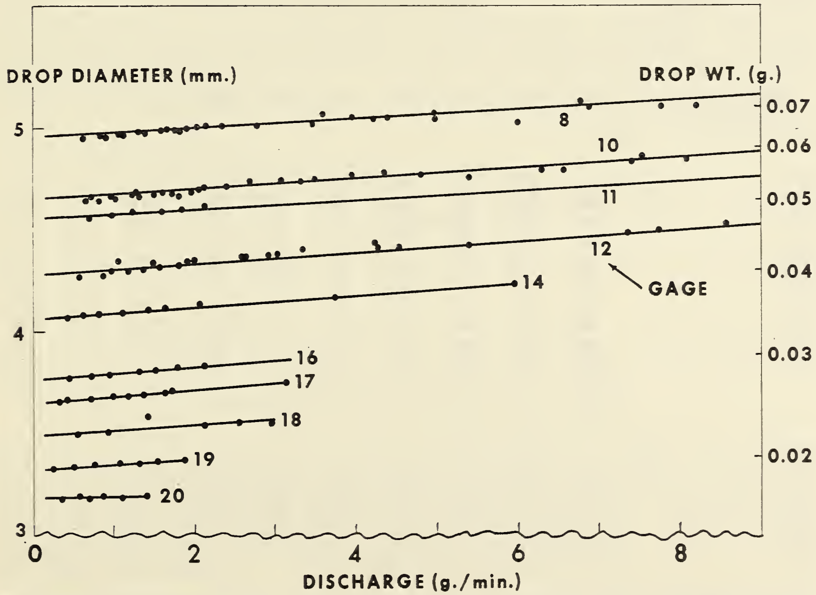

FIGURE 4.—Relation of drop diameter and gage of outlet orifice to discharge rate from graded tubes.

gested extrapolations of the discharge relationships to drop diameters for those cases in which data are scanty or missing are indicated by the dashed lines.

Figure 4 reproduces parts of figure 3 where the drop diameter appears to be linearly related to discharge. These data may be used to guide the operation of the laboratory rainfall simulator. The graph shows that average drop diameters of 3.2 mm. to 5.2 mm. can be produced by graded tubes without exceeding a discharge rate of 9 grams per minute.

The significance of being able to produce 5-mm. drops under controlled conditions becomes apparent when the criteria proposed by Wischmeier and Smith (*14*) are considered. They suggest that rainfall effects on soil loss be based on one-hundredth of the product of the rainfall energy E for a given storm and the maximum 30-minute intensity of the storm I. Using this criterion, it is more important to simulate storms based on the EI value, rather than intensity or amount of water. The availability of large drops is essential when the height of fall is limited. The additional mass of large drops is needed to compensate for the failure of the falling drops to reach terminal velocity. Drops as large as 20 mm. in diameter have been produced in the laboratory by Magarvey and Taylor (*7*). However, Blanchard (*2*) has found that any drop above 5.5 mm. in diameter is extremely unstable.

Recognizing that the drop-size distribution is highly correlated with the storm intensity in natural rainfall, Wischmeier, Smith, and Uhland (*15*) derived an energy equation to express kinetic energy as a function of rainfall intensity. The values shown in table 2, multiplied by the inches of rain falling at the rate selected, describe the

TABLE 2.—*Kinetic energy of natural rainfall in foot-tons per acre-inch* [1]

Rainfall (inches per hour)	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0	-----	254	354	412	453	485	512	534	553	570
0.1	585	599	611	623	633	643	653	661	669	677
0.2	685	692	698	705	711	717	722	728	733	738
0.3	743	748	752	757	761	765	769	773	777	781
0.4	784	788	791	795	798	801	804	807	810	814
0.5	816	819	822	825	827	830	833	835	838	840
0.6	843	845	847	850	852	854	856	858	861	863
0.7	865	867	869	871	873	875	877	878	880	882
0.8	884	886	887	889	891	893	894	896	898	899
0.9	901	902	904	906	907	909	910	912	913	915
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	916	930	942	954	964	974	984	992	1, 000	1, 008
2	1, 016	1, 023	1, 029	1, 036	1, 042	1, 048	1, 053	1, 059	1, 064	1, 069
3	1, 074	1, 079	1, 083	1, 088	1, 092	1, 096	1, 100	1, 104	1, 108	1, 112
4	1, 115	1, 119	1, 122	1, 126	1, 129	1, 132	1, 135	1, 138	1, 141	1, 144
5	1, 147	1, 150	1, 153	1, 156	1, 158	1, 161	1, 164	1, 166	1, 169	1, 171
6	1, 174	1, 176	1, 178	1, 181	1, 183	1, 185	1, 187	1, 189	1, 192	1, 194

[1] From table 1, p. 286, of reference (*14*).

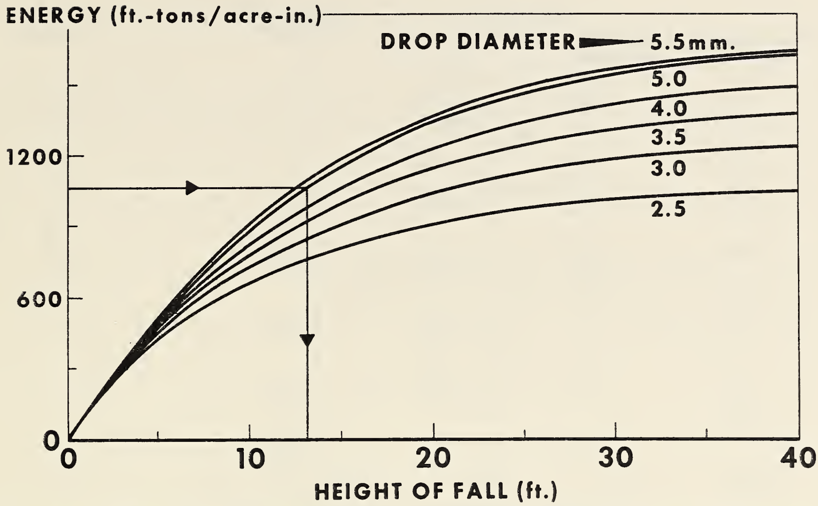

FIGURE 5.—Relation of kinetic energy to height of fall for various diameter waterdrops.

energy value for a particular increment of a natural storm. These same values may be used to determine the amount of kinetic energy that artificially formed waterdrops should produce to simulate a particular rainstorm.

Figure 5 shows the relation between the kinetic energy produced and the height of fall for various size waterdrops. The fall velocities used to calculate kinetic energy were based on data by Laws (*6*). For a given storm, the kinetic energy to be simulated can be determined from table 2, and when ceiling heights limit the height of fall figure 5 can be used to determine the size of drop required to simulate the storm desired.

For example, assume that an application intensity of 3 inches per hour for 1 hour is desired, using drops having a 5.0-mm. diameter. The kinetic energy to be produced, using table 2, is found to be 1,074 foot-tons per acre-inch. Figure 5 shows that a height of fall of 13.3 feet will provide the desired energy at impact, with 5.0-mm. diameter drops.

The total energy for the simulated storm is 1,074 $\times$ 3, or the product of the energy value from table 2 and the inches of rain that fall within the time increment. The *EI* value would, therefore be (1,074 $\times$ 3) $\times$ 3 $\div$ 100 = 96. 66.

The design of the applicator for the rainfall simulator can be facilitated by means of the nomograph shown in figure 6. The nomograph assumes that the radius of the applicator is 27 inches, less 3 inches at the center for housing a shaft. The total area of the applicator is 2,260.8 square inches, or 14,585.5 square centimeters. Water must be applied at the rate of 617.45 grams per minute to simulate 1 inch per hour of rainfall.

If it is assumed that the applicator is to apply water through 300 graded tubes at 3 inches per hour, from the nomograph, each graded

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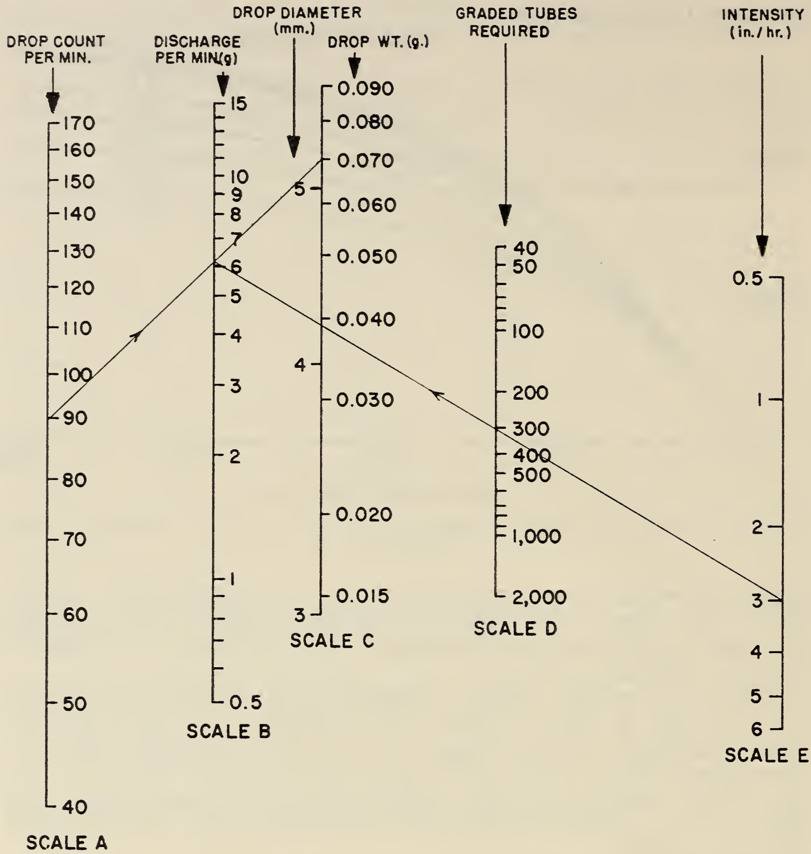

FIGURE 6.—Nomograph to compute count per minute, discharge rate per minute, waterdrop diameter, waterdrop weight, graded tubes required, and intensity of a given storm for an applicator unit covering 2,260.8 square inches (27-inch radius).

tube should discharge 6.2 grams of water per minute. Figure 1 indicates that a 21 to 8 graded tube under a head of 14.5 cm. will provide this rate of discharge. Figure 2 shows that this graded tube will produce 89 drops per minute under a 14.5-cm. head. The nomograph shows that the drop size will be 5.10 mm. in diameter.

If 200 graded tubes were used, it would require a discharge of 9.35 grams per minute from each graded tube, and a 11.35-cm. head for the 20 to 8 graded tube, to obtain a drop count of 129 per minute and to produce a 5.17-mm. diameter drop.

For a circular applicator the graph in figure 7 may be used to locate the position of the various graded tubes. The applicator has been arbitrarily divided into eight sections; the line marked 50 indicates a total of 400 graded tubes. The position number refers to the placement of the graded tube away from the center of the unit. For example, if eight sections of 50 tubes each are to be used, the first

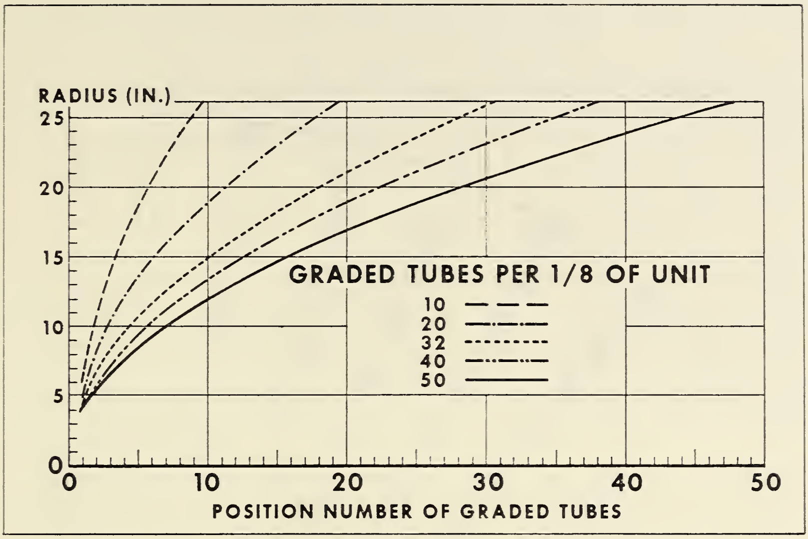

FIGURE 7.—Radius position that will provide equal area distribution for a given number of graded tubes.

tube should be placed 3.9 inches from the center, tube number 30 should be on the 20.8-inch radius.

To minimize a drop furrow effect on the soil pans, each one-eighth section should have a different tubing arrangement. This can be most easily accomplished by varying the number of graded tubes in each section about the mean of the required number. One arrangement for locating the graded tubes is shown in figure 8, for a one-eighth section of the applicator. The other seven sections are shown in figures 14 to 20, in the appendix. If this arrangement is used, rainfall intensities from 1 to 5 inches per hour can be simulated.

Table 3 shows the height of head in centimeters that will provide intensities of 1 to 5 inches of rainfall per hour and the distance above

TABLE 3.—*Head and height of fall to simulate various rainfall intensities* [1]

Rainfall (inches per hour)	Graded tube	Tubes	Head (h)	Height of fall
	Gage	*Number*	*Centimeters*	*Feet*
1	21 to 8	100	14.5	10.4
2	21 to 8	300	8.9	12.0
3	21 to 8	300	14.5	13.1
4	21 to 8	300	20.3	13.9
4	20 to 8	300	9.5	13.9
5	21 to 8	300	12.8	14.6

[1] See table 5, appendix, for worksheet.

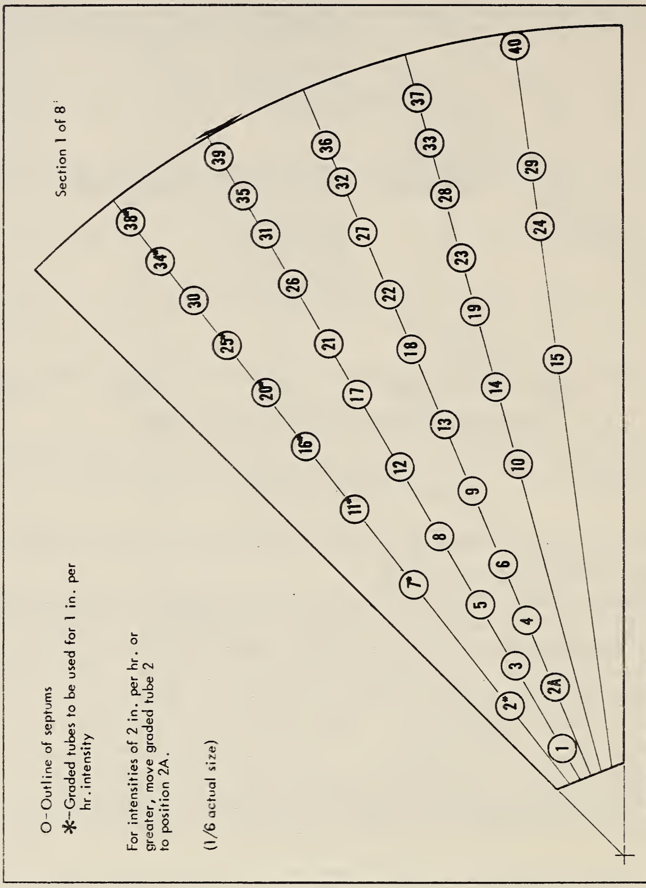

FIGURE 8.—Graded tube arrangement for applicator unit divided into 8 sections: Section 1.

the reference plane at which the applicator should be set. A work sheet (table 5) for table 3 is in the appendix, p. 21.

The nomograph and other graphs were provided to facilitate the design of the applicator without requiring considerable recomputation. However, separate calibration of the graded tubes is necessary to provide precision, and careful computations should be made to eliminate any error that may arise from reading the graphic data.

JET FLOW AND ITS BREAKUP

In the preceding section, studies showed that drops of a desirable size for rainfall simulation (1.24 mm. to 4.44 mm. in diameter) can be produced by the disintegration of a water jet, but jet flow was accompanied by a high discharge rate. This method of drop formation could not, therefore, be readily utilized in the design of the applicator for the laboratory rainfall simulator that was planned. The graded tube was developed to produce the desired drop size while limiting the discharge rate.

The first attempt to form drops from the water column described in the appendix (p. 17) involved jet flow. Since water jets may be of future value in simulating rainfall, some consideration was given to the nature of this type of drop formation.

A liquid jet is considered to be unstable when any disturbance impressed upon the jet at the orifice is of a wavelength (λ) that is greater than the circumference of the jet. The waves produced by the disturbance travel downward, and their amplitude grows exponentially until the sides of the jet come together, forming separate drops. Rayleigh (*10*) has shown that the time that elapses before this occurs depends on the initial amplitude of the disturbance and upon the rate at which it grows.

Smith and Moss (*12*) produced jets of mercury and other fluids, including water, using vertical glass tubes. When plotted, their data formed characteristic curves, expressing the relationship of the jet length (l) to the head (h) above the orifice, which are similar to the curves shown in figure 9 for two different lengths of 17-gage stainless steel tubing.

The idealized curve in the block of figure 9 shows that at A, jet formation first occurs. The jet length increases rapidly until point B, the lower critical head, is reached. At B, the slope decreases and remains practically constant to point C, the upper critical head, which has a Reynolds number (R_n) of approximately 2,000. Beyond C the jet length decreases erratically as the head increases, until point D is reached. Between D and E the rate of decrease is small. The waveform of the amplitude of the disturbance at the orifice tending to cause disintegration is considered to be varicose to the upper critical velocity, and sinuous beyond. Its shape depends on which force, surface tension or viscosity, controls at a given point.

Smith and Moss (*12*) note that if a is the initial amplitude, a_o the

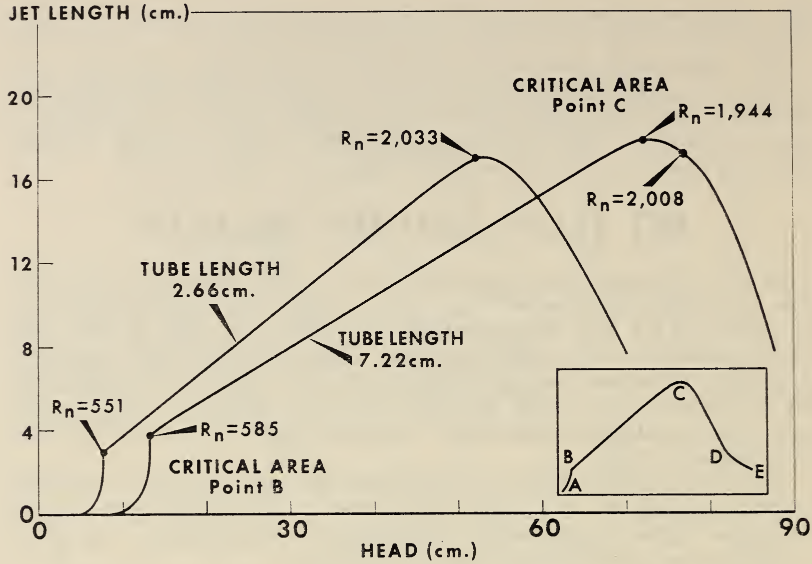

FIGURE 9.—Relation of jet length to head of water for 2 lengths of 17-gage tubing, and idealized curve showing relation of jet length to head of water above a small tube.

value that it has to acquire before disintegration occurs, t the time required, and q a constant, then

$$a_o = ae^{qt}$$

or

$$t = l/q(\log_e a_o/a)$$

Based on their experimental results, Smith and Moss show that the ratio a_o/a is constant. They point out that the initial amplitude may be a constant fraction of the diameter of the jet.

Tyler and Richardson (*13*) demonstrated the effects of differences caused by nozzle characteristics. They showed that surface tension may be predominant in the *ABC* portion of the curves, but that viscosity has greater influence in the *CDE* portion. Both surface tension and viscosity affect disruption at a definite point in the jet, the actual jet length depending on the controlling force. At point *C* either of these forces may disrupt the jet.

Tyler and Richardson suggest that the abnormally low values of l when v is small are caused by ripples that traverse the jet reacting on the nozzle. This additional disturbance tends to break up the jet sooner than if the ripples were unable to reach the nozzle. Since the drops are formed very close to the nozzle, this may be a further contribution toward disintegration in an unusually short time. At higher velocities, a distinct "neck" is formed just outside the nozzle, which seems to prevent the effects of turbulence from working up to the nozzle.

Merrington and Richardson (*8*) concerned their investigation primarily to the size and behavior of drops subsequent to the breakup of the jet from stationary and moving nozzles. Their results for various fluids show that when jet breakup occurs in the sinuous portion of the characteristic curve, or "atomization stage," the expression

$$Vd/\mu^{1/5}=500$$

may be used to predict the mean drop size, where V is the relative velocity between the jet and the surrounding air, d is the mean drop size, and μ is the kinematic viscosity of the liquid. Their experiments show that at low velocities the mean drop size reaches a constant value that is roughly twice the nozzle diameter. They report that only drops less than 0.25 mm. in diameter require correction for evaporation when dropped from 50 feet.

Bear in mind that the principal objective of this research was to develop a drop-forming device; the concern and interest in jet formation evolved from experimentation. Although the jet length could be measured to the nearest tenth of a centimeter with a steel scale, no precision instrument was available to measure the jet diameter. Verification of the Merrington-Richardson formula was not made.

Since the number of drops formed of a given size within a fixed time-interval depends on the jet discharge from which the drops are formed, attention was directed toward measuring jet discharge as a means of comparing tubing samples.

To determine the number of different samples of a given length and diameter that are required to assure consistent discharge results, eight lengths of four different gage sizes (17, 14, 13, and 11) were cut 2.85 inches long on a small lathe. The length was arbitrarily chosen. Sharp-edged orifices were machined at each end of the tube.

If it is assumed that variations in environmental conditions can be controlled and that the instrumentation is adequate to measure the discharge, the differences in discharge values may be attributed to variations in the tubing.

Tyler and Richardson (*13*) have demonstrated the considerable influence that variations in nozzle characteristics have on jet flow. The fabrication of the sample lengths of tubing could introduce these variations. Manufacturers of the tubing maintain quality control by weighing sample lengths of tubing. As measurements were not available for the specific tubing supplied and instruments were not available to measure tubing wall thicknesses, the measure of interaction between the characteristics of the manufactured tubing and the fabrication of the tubing was not attempted.

Average discharge values and drop counts were taken for various combinations of head, tubing diameter, and tubing length. The rate of drop formation ranged from 15,200 to 23,500 drops per minute for water jets occurring beyond the critical point B in figure 9. However, the mean drop count for 148 test runs was 19,981 drops per minute with a standard error of ± 113 drops per minute.

The size of drop formed by the breakup of a water jet issuing from a small tube can be estimated by dividing the average rate of drop formation into the discharge rate. Figure 10 was evolved for estimating the discharge from a sharp-edged stainless steel tube of a

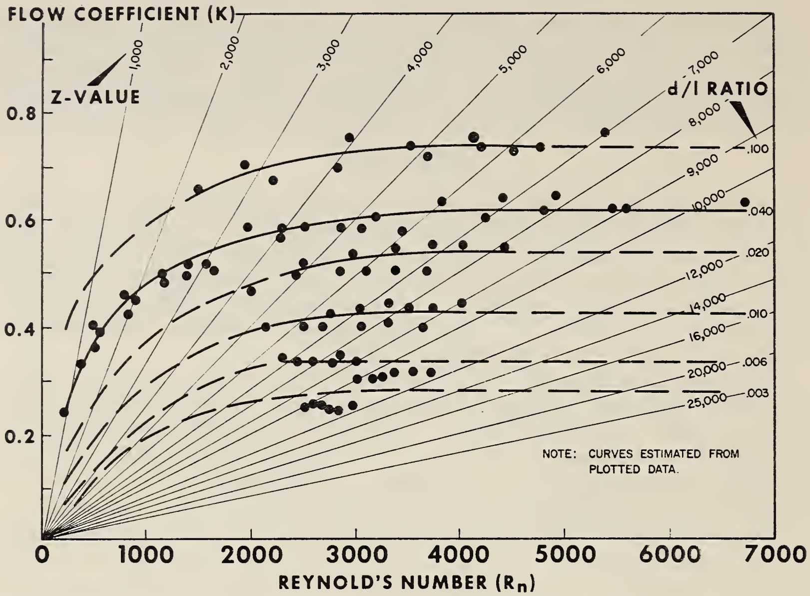

FIGURE 10.—Flow coefficients for sharp-edged stainless steel tubes related to ratio of diameter to length of tube and Reynolds number.

given diameter and length under a fixed head. Results obtained by using this graph have an average deviation of experimental from theoretical values of less than 5 percent. The lines representing the Z values in figure 10 are computed and shown as solid lines. The solid portions of the d/l lines represent experimental data, whereas the dashed lines are estimated extensions of these lines.

The variables are represented by the following symbols:

d=diameter of tubing, in centimeters
g=gravitational constant, in centimeters per second-squared
h=head above orifice, in centimeters
l=length of tube, in centimeters
q=discharge, in grams per second
ρ=density of fluid, in grams per cubic centimeter
μ=dynamic viscosity of fluid, in grams per centimeter-second
A=cross-sectional area of tube, in centimeters-squared
d_w=drop weight, in grams

To estimate the discharge, enter the graph from the right with the d/l ratio and from the top with the Z value computed from

$$Z=\frac{\rho d}{\mu}\sqrt{2gh}$$

At the point of intersection read off the values of Reynolds number (R_n) and the flow coefficient (K). The value of q may be calculated from the expression

$$q=KA\sqrt{2gh}$$

The average weight of a drop (d_w) formed at breakup may be estimated from the expression

$$d_w \approx q/20{,}000$$

In these experiments the rate of change in average drop size with increasing head is noted to be greatest under low heads below point *B* in figure 9. Beyond this point the drop count is close to being constant, and changes in discharges are reflected in a change in drop size, rather than a change in the number of drops formed.

SUMMARY

An apparatus for forming waterdrops that range from 3.2 mm. to 5.2 mm. in diameter is described. In order to utilize the experimental results, criteria are presented that may be used in designing a laboratory rainfall simulator. Some observations on the breakup of water jets are reported, and flow coefficients are provided to predict the discharge from a given length and diameter of stainless steel tubing under certain head conditions.

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APPENDIX

Drop Counting and Collecting Apparatus

The apparatus shown in figure 11 was designed to simultaneously count and collect waterdrops discharging from small stainless steel tubes while the collection period was automatically timed.

Head Control.—A 36-inch length of Pyrex glass pipe 3 inches in diameter was sealed at one end by a professional glass blower. A hole was drilled in the center of the closed section to accept a septum the same size as a No. 1 stopper. The thin, self-sealing, membrane core of the septum can be easily pierced by the small-diameter, stainless steel tubing. The water column level is maintained at a designated head by means of a double-siphon system to a supply of distilled water. Once the head is established at the desired level, the tubing being studied is permitted to discharge continuously. The level of the double-siphon system is maintained by using an overflow tube ⅜ inch in diameter, which is much larger than the tubing under test in the water column. A sump pump replenishes the supply of distilled water being circulated.

Drop Counting.—The counting unit consists of a cold cathode, photo-multiplier counting tube, and a high-speed magnetic counter. It is capable of counting up to 30,000 impulses per minute, with a short

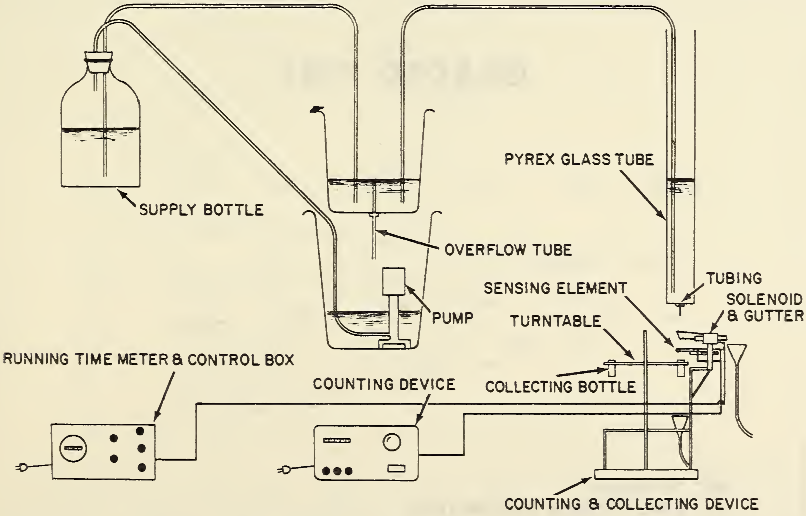

FIGURE 11.—Diagram of an apparatus designed to count, collect, and time the collecting period when waterdrops are discharged through small stainless steel tubes.

pulse length of 0.0002 second. Transistors are used to eliminate warmup-time delays that might adversely affect reliability. A No. 62 drill was used to place a hole in the center of a snug-fitting aluminum mask that concentrates the light source.

An aluminum gutter is located between the discharging orifice and the photo-multiplier unit. The position of the gutter is controlled by a solenoid, so that it catches the issue and carries it off to a bypass reservoir. When a count is to be made, the solenoid is activated, moving the gutter out of the vertical path of the drops. The drops then pass between the light source and sensing element of the photo-multiplier unit. A running-time meter is in the same circuit as the solenoid. While the drops are being counted, the running-time meter measures the test period to the nearest 0.1 second. At the end of the test period, the gutter is simultaneously interspaced between the discharging orifice and the photo-multiplier unit as the running-time meter is stopped.

Drop Collection.—The drops fall into a weighing bottle after they are counted. A turntable that can hold eight bottles is moved manually into position before the test period starts. After collection the time-interval, drop count, and temperature are recorded. The sample is then weighed on an analytical balance, and the average weight and average number of individual drops are calculated.

Fabricating the Graded Tubes

Figure 12 illustrates a 21 to 8 graded tube. The segments used to make this tube and all other tubes were cut 1.5 cm. long. Both ends

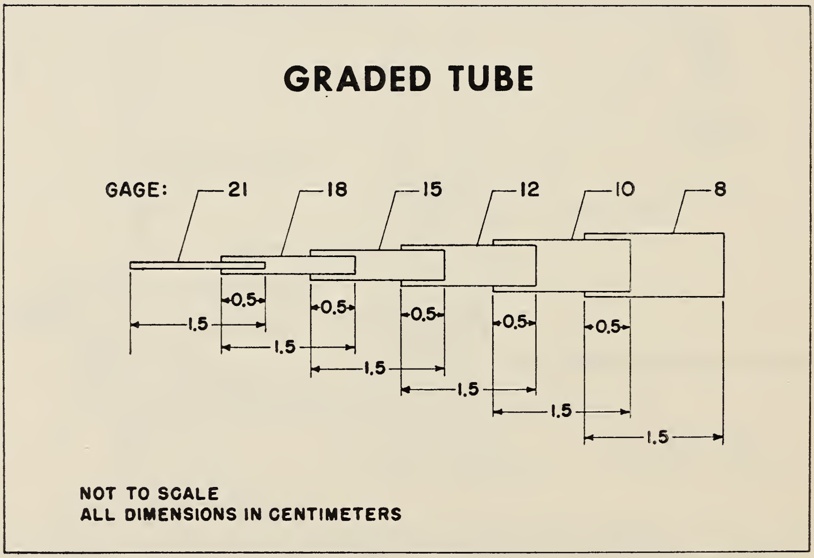

FIGURE 12.—Diagram of a graded tube.

of each segment were machined on a lathe to a sharp edge. Table 4 lists the graded tubes fabricated for this study. The headings represent the gage size of the terminating orifice.

Two methods of soldering the segments will assure good results. The first procedure utilizes solid solder; the second, a solder paste.

TABLE 4.—*Makeup of graded tubes*

Tube designation	Gage tubing (see table 1) [1]
Eights	24, 20, 17, 14, 12, 10, 8
	23, 19, 16, 13, 10, 8
	22, 18, 15, 12, 10, 8
	21, 18, 15, 12, 10, 8
	20, 17, 14, 12, 10, 8
Tens	24, 20, 17, 14, 12, 10
	23, 19, 16, 13, 10
	22, 18, 15, 12, 10
	21, 18, 15, 12, 10
	20, 17, 14, 12, 10
Elevens	23, 19, 16, 13, 11
	19, 16, 13, 11
Twelves	24, 20, 17, 14, 12
	22, 18, 15, 12
	21, 18, 15, 12
	20, 17, 14, 12
Thirteens	23, 19, 16, 13
	19, 16, 13
Fourteens	24, 20, 17, 14
	20, 17, 14
Fifteens	22, 18, 15
	21, 18, 15
Sixteens	23, 19, 16
	19, 16
Seventeens	24, 20, 17
	20, 17
Eighteens	21, 18
	22, 18
Nineteens	23, 19
Twenties	24, 20

[1] All segments of tubes were cut 1.5 cm. long.

The graded tubing can be joined by a 60:40 lead–tin solder and a stainless steel flux. The solder must first be pressed flat and cut into thin strips. This assures that little heat will be required to cause it to flow. A hotplate provides an adequate amount of heat

when an aluminum or similar metal disk is placed on it. The segments to be joined are placed on the aluminum disk, flux is applied, and when sufficiently heated (5 to 10 seconds) they are soldered. The operation is quick and if the soldered segment is moved off the hotplate, the joint will hold without difficulty.

Another method is to use a silver solder paste between each joint, set the entire graded tube on a fire-resistant surface, and brush the

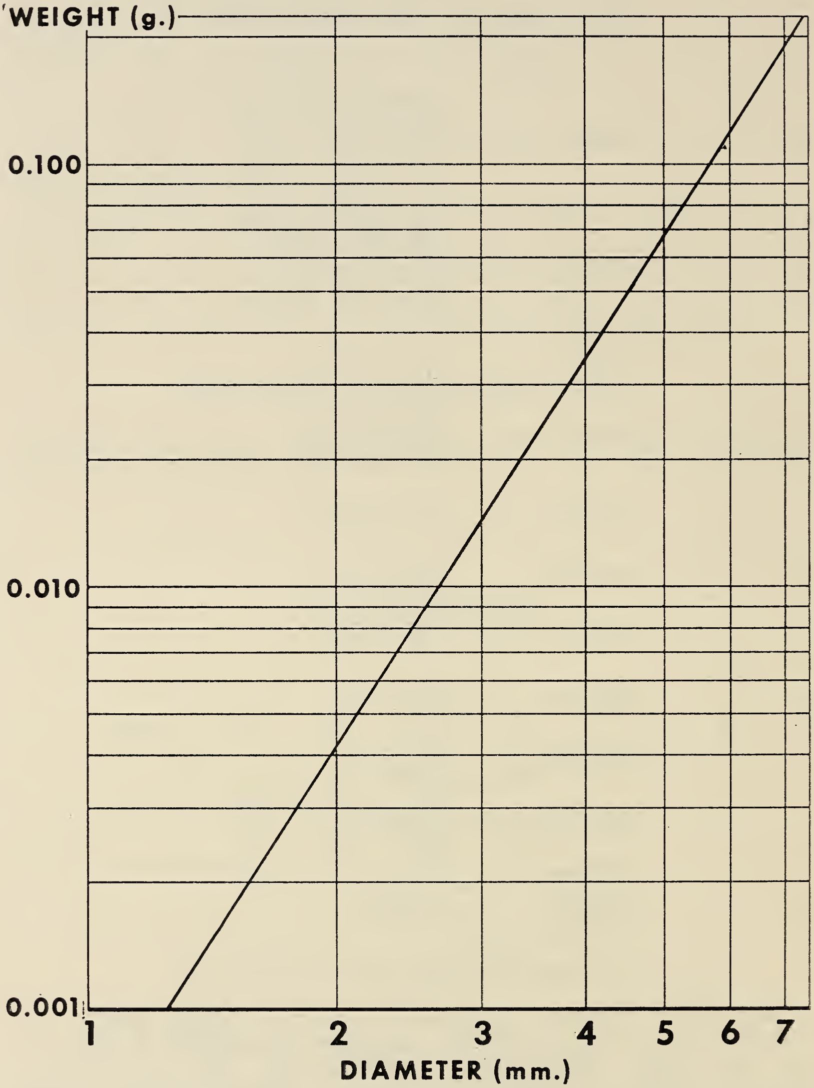

FIGURE 13.—Plot of the nominal drop diameter to drop weight used to convert size to weight.

flame from a small propane torch over its entire length. This method is more readily adapted to producing a large number of graded tubes.

Figure 13 is a plot of the nominal drop diameter to drop weight, for ease in converting size to weight.

Table 5 is a worksheet to aid in determining values similar to those in table 3, p. 9.

TABLE 5.—*Worksheet for table 3* [1]

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Rainfall intensity (*I*)	Tubes	Discharge per tube	Graded tube	Head (*h*)	Drop			Kinetic energy, natural rain	Height of fall to simulate rain	Kinetic energy, for one hour	*EI* value
					Count	Weight	Diameter				
In./hr.	*Number*	*G./min.*	*Gage*	*Cm.*	*Number*	*G.*	*Mm.*	*Foot-tons per acre-inch*	*Ft.*	*Foot-tons per acre-inch*	*Foot-tons per acre-inch*
1	100	6.2	21 to 8	14.5	89	0.0693	5.10	916	10.4	916	9.16
2	300	4.1	21 to 8	8.9	59	.0698	5.11	1,016	12.0	2,032	40.64
3	300	6.2	21 to 8	14.5	89	.0693	5.10	1,074	13.1	3,222	96.66
4	300	8.2	21 to 8	20.3	117	.0703	5.12	1,115	13.9	4,460	178.40
4	300	8.2	20 to 8	9.5	115	.0716	5.15	1,115	13.9	4,460	178.40
5	300	10.3	21 to 8	12.8	141	.0730	5.18	1,147	14.6	5,735	286.75

[1] Explanation according to column number: After each column explanation, an example based on a 3-inch per hour intensity is discussed.

(1) This is the rainfall intensity (*I*) to be simulated. Insert 3 inches per hour in column 1 and determine values for other columns.

(2) and (3). These are the paired values for the number of tubes and discharge rate per tube to produce the desired (*I*) that can be determined by using figure 6. Place a straightedge on scale *E* at 3 inches per hour and extend it through the paired values of scales *B* and *D*. In the example 300 tubes have been selected and each tube should discharge 6.2 grams per minute.

(4) The graded tube or tubes that will produce the discharge rate shown in column 3 may be found by referring to figure 1. The 6.2 grams per minute discharge previously determined can be produced by a 21 to 8 graded tube.

(5) This is the head required to produce the discharge rate shown in column 3. This head is also found from figure 1. The discharge of 6.2 grams per minute through a 21 to 8 graded tube occurs under a head of 14.5 cm.

(6) The number of drops per minute formed by the selected graded tube under the head shown in column 5 is found by using figure 2. The drop count for a 21 to 8 graded tube under a 14.5-cm. head is 89 drops per minute.

(7) and (8). The nominal drop diameter and average drop weight can be read off the nomograph. Pass a straightedge through the drops per minute scale *A* and discharge rate scale *B* and read the drop diameter and weight on scale *C*. The average drop has a nominal diameter of 5.10mm. and weighs 0.0693 gram.

(9) The kinetic energy of natural rainfall for the desired intensity (*I*) may be located in table 2. A 3-inch per hour intensity produces 1,074 foot-tons per acre-inch.

(10) The height of fall necessary to achieve the kinetic energy value may be found from figure 5. A drop with a nominal diameter of 5.10 mm. will produce 1,074 foot-tons per acre-inch (I=3 inches per hour) when the height of fall is 13.1 feet.

(11) The kinetic energy for a storm increment is found by multiplying the kinetic energy value shown in column 9 by the intensity for the period over which the intensity occurs. The kinetic energy produced by a 3-inch per hour storm over a period of one hour is 1,074×3×1, or 3,222 foot-tons per acre-inch.

(12) The *EI* value for the storm increment is the product of column 11 and 1, divided by 100. *EI* is, therefore, 3,222×3÷100, or 96.66 as shown in this column.

Figures 14 through 20 show the remaining seven sections of the applicator.

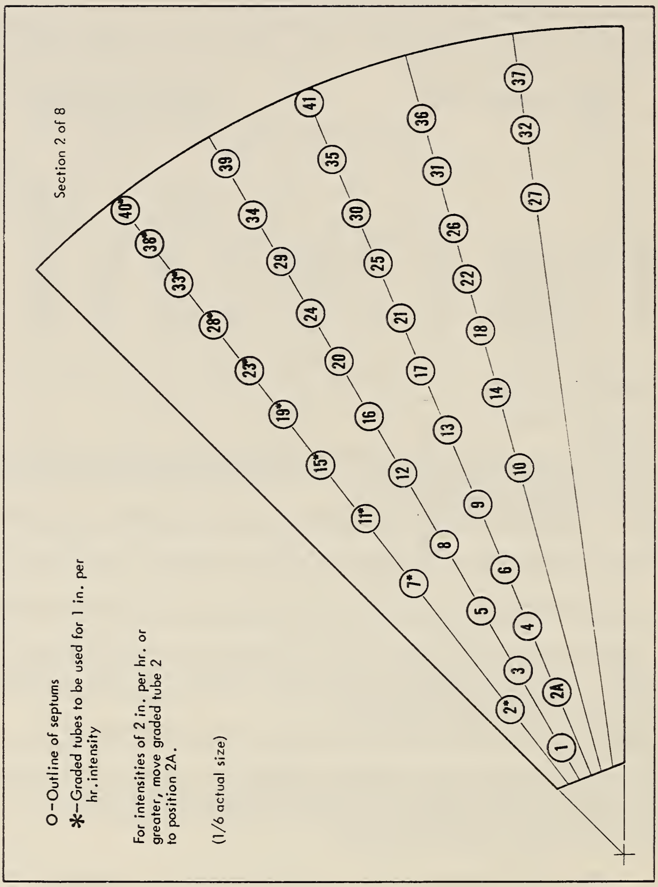

FIGURE 14.—Graded tube arrangement for applicator unit: Section 2.

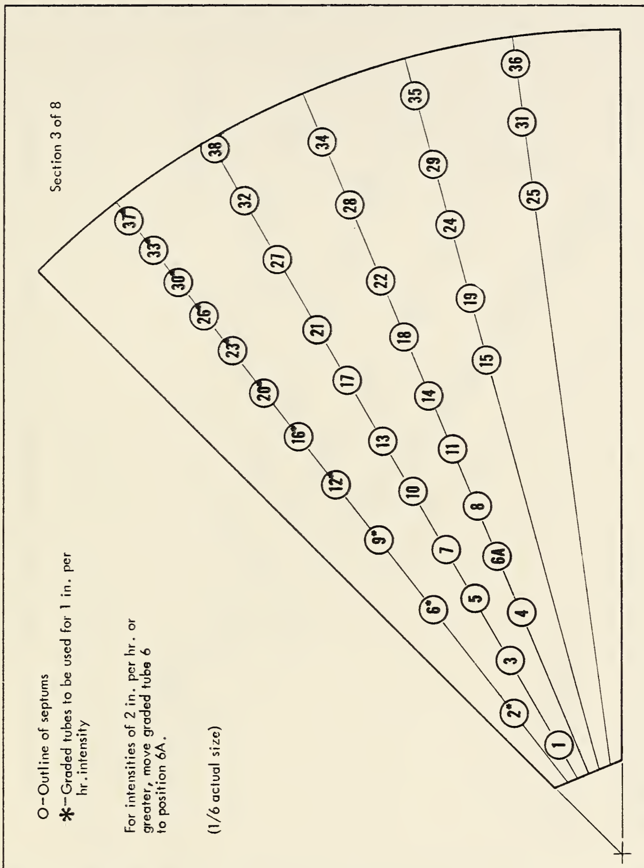

FIGURE 15.—Graded tube arrangement for applicator unit: Section 3.

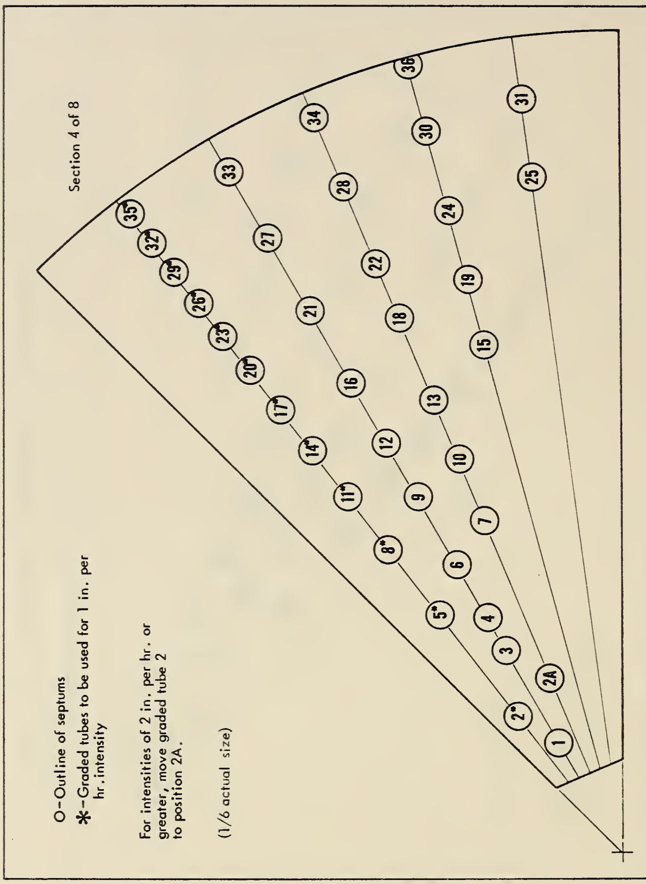

FIGURE 16.—Graded tube arrangement for applicator unit: Section 4.

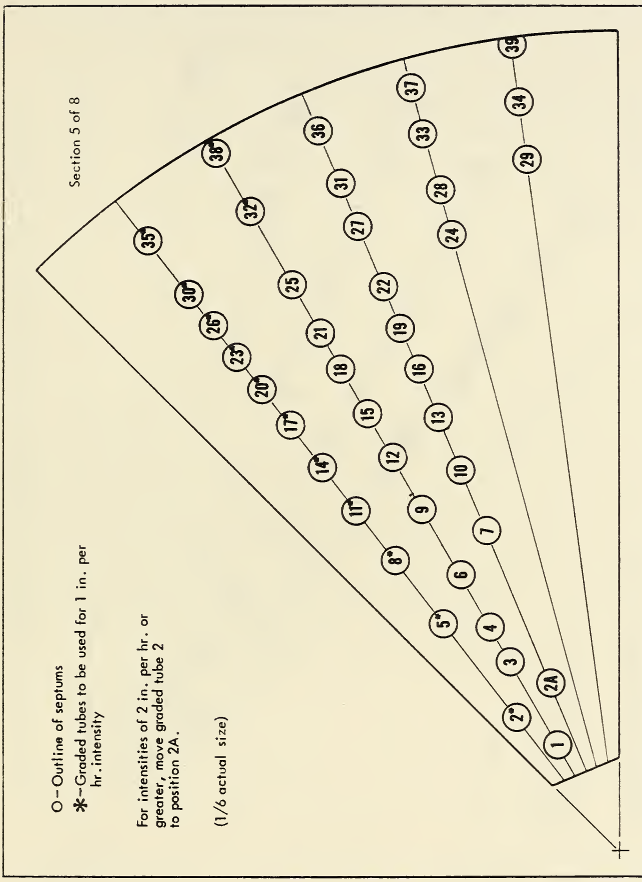

FIGURE 17.—Graded tube arrangement for applicator unit: Section 5.

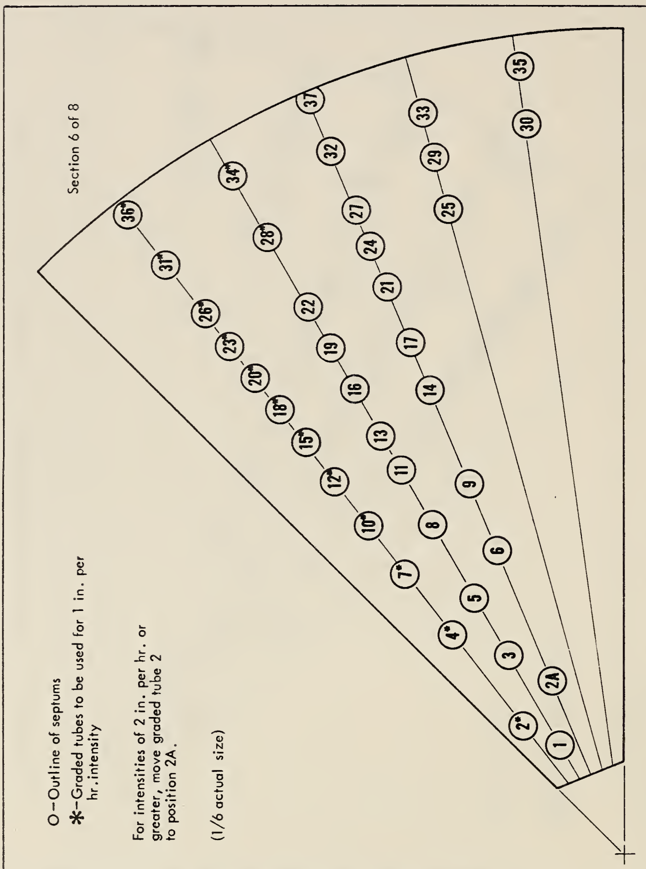

FIGURE 18.—Graded tube arrangement for applicator unit: Section 6.

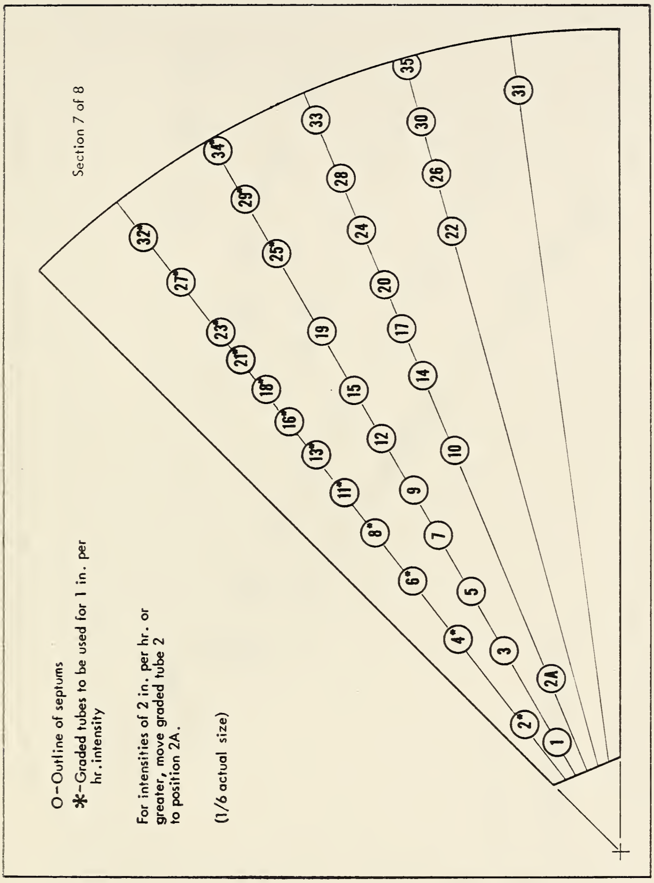

FIGURE 19.—Graded tube arrangement for applicator unit: Section 7.

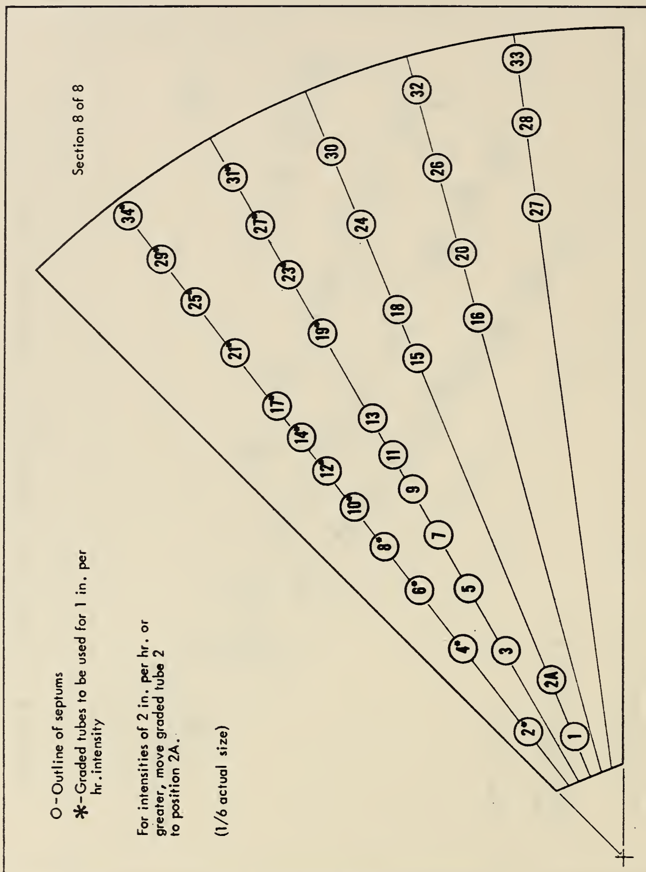

FIGURE 20.—Graded tube arrangement for applicator unit: Section 8.

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